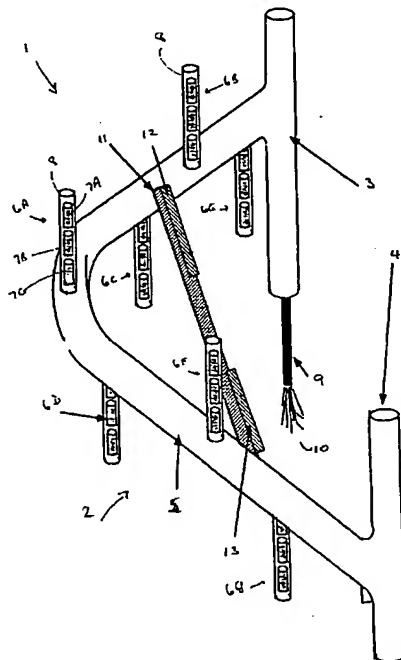(72) TULLMIN, Martin, CA
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(54) **SONDE DE CONTROLE DE LA CORROSION POUR STRUCTURES EN BETON ARME**

(54) **CORROSION MONITORING PROBE FOR REINFORCED CONCRETE STRUCTURES**

(57) A corrosion measuring system for assessing of the onset and rate of corrosion of reinforcing steel embedded in a concrete structure having an exterior surface. The system comprises a set of at least three elements formed from reinforcing steel and located in a spaced apart relationship at the same depth from the exterior surface. Each of the elements has electrical connections extending therefrom through the exterior surface. The electrical connections are adapted for connection to apparatus for measurement of electrochemical properties of the elements for assessment of corrosion of said reinforcing steel. Preferably, there is additionally at least one element of electrical conductive material less susceptible to corrosion in concrete that is also embedded. There are preferably more than one set of the at least three elements, each set being located at differing distances from the exterior surface.

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ABSTRACT OF THE DISCLOSURE

A corrosion measuring system for assessing of the
onset and rate of corrosion of reinforcing steel embedded
5   in a concrete structure having an exterior surface. The
system comprises a set of at least three elements formed
from reinforcing steel and located in a spaced apart
relationship at the same depth from the exterior surface.
Each of the elements has electrical connections extending
10   therefrom through the exterior surface. The electrical
connections are adapted for connection to apparatus for
measurement of electrochemical properties of the elements
for assessment of corrosion of said reinforcing steel.
Preferably, there is additionally at least one element of
15   electrical conductive material less susceptible to
corrosion in concrete that is also embedded. There are
preferably more than one set of the at least three
elements, each set being located at differing distances
from the exterior surface.
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Corrosion Monitoring Probe
For Reinforced Concrete Structures

The present invention relates to a corrosion
5 monitoring probe that may be installed in reinforced
concrete structures, and especially to a corrosion
monitoring probe that may be utilized in a variety of
measurements relating to the monitoring of corrosion of
reinforcing steel in concrete structures. In particular,
10 a corrosion measuring system is provided for assessing
both the onset and the rate of corrosion of reinforcing
steel in concrete structures.

Concrete structures typically have steel reinforcing
bars, frequently referred to as rebar, which may be in a
15 variety of shapes and sizes, including steel girders,
rods or other reinforcing parts formed of steel. Good
quality, sound concrete structures provide an ideal
environment for steel reinforcing bar i.e. rebar, because
the high pH of the cement paste pore solution in the
20 concrete passivates the steel, reducing the natural
corrosion rate of the steel to insignificant levels,
typically less than 1 micron (micrometre) per year. Such
protection against corrosion does not depend upon the
impermeability of the concrete, but on the high pH of the
25 cement pore solution which forms a thin firmly bonded
oxide layer on the surface of the steel. The oxide layer
provides sufficient protection to permit the use of steel
in many structures that are exposed to weathering.

However, under some conditions, the oxide layer on
30 the steel may be broken down, permitting corrosion to
occur. For instance, chloride ions from marine
atmospheres or from de-icing salts that are applied to
roads in winter can penetrate the concrete cover and
break down the passivity of the steel, thereby permitting
35 active corrosion to occur. In addition, reactions may
occur between the cement paste and atmospheric carbon
dioxide or other acidic gases, which causes a reduction

in the pH of the cement paste pore solution to a level at which the steel readily corrodes. Carbonation and chloride attack can occur independently or can act in synergy.

5   Corrosion has two detrimental consequences. Firstly, it reduces the cross-section and thereby the load- bearing capacity of the rebar. Secondly, the corrosion products tend to occupy a much larger volume than the steel from which they are formed, causing

10   tensile stresses in the concrete that result in cracking and spalling of the concrete cover. As used herein, the concrete cover is the layer of concrete covering the outer layer of rebar through which aggressive species e.g. chlorides, must be transported in order to initiate

15   rebar corrosion.

      The lifetime of a reinforced concrete structure exposed to chlorides and/or carbonation can be described, in the absence of preventative maintenance, as consisting of two periods. The first period is one in which there

20   is no active corrosion but aggressive species such as chlorides or carbon dioxide penetrate the concrete cover. The second period starts at corrosion initiation and continues until the damage to the concrete and steel are sufficient to warrant remedial action.

25   U.S. Patent No. 5,015,355 of P. Schiessel describes a corrosion measuring cell that has several electrodes consisting of structural steel or reinforcing steel arranged at different distances from the external surface of the concrete structural part. Each of these

30   electrodes are connected to the electrode functioning as a cathode e.g. a more noble material, via a measuring element. This allows for macrocell measurements described below.

      A corrosion monitoring system that is adaptable for

35   use with a variety of measurement techniques has now been found, and especially provides for measurement techniques to assess both the onset of corrosion and the rate of

corrosion.

Accordingly, an aspect of the present invention
provides a corrosion measuring system for assessment of
the onset and rate of corrosion of reinforcing steel
5   embedded in a concrete structure having an exterior
surface, comprising:

(a)   a set of at least three elements formed from
said reinforcing steel and located in a spaced apart
relationship at the same depth from said exterior
10 surface;

(b)   each of said elements having electrical
connections extending therefrom through said exterior
surface, said electrical connections being adapted for
connection to apparatus for measurement of
15 electrochemical properties of said elements for
assessment of corrosion of said reinforcing steel.

In a preferred embodiment of the corrosion measuring
system of the present invention, there is additionally at
least one element of electrical conductive material less
20 susceptible to corrosion in said concrete, said
electrical conductive material being embedded in said
concrete and having an electrical connection extending
through said exterior surface adapted for connection to
said apparatus.

25 In another embodiment, there are more than one set
of said at least three elements, each of said sets of at
least three elements being located at differing distances
from said exterior surface.

In a further embodiment, said elements are located
30 on corrosion-resistant electrically non-conductive
supports.

In yet another embodiment, said supports are tubular
and said electrical connections pass through said tubular
support.

35 In still another embodiment, a reference electrode
and/or a hygrometer is embedded in the concrete.

In another embodiment, said electrically non-

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conducting supports are further supported by a second
electrically non-conductive tubular support that is
attached to said reinforcing steel, said electrical
connections passing through said second tubular support

5   to said exterior surface.

In yet another embodiment, the distance between
adjacent sets of elements is 5-15 mm, as measured from
said exterior surface.

The present invention will be illustrated with

10   reference to the embodiments shown in the drawings, in
which:

Figure 1 is a schematic representation of a
corrosion monitoring system of the invention;

Figure 2 is a schematic representation of another

15   corrosion monitoring system of the invention;

Figure 3 is a schematic representation of
measurements using a set of elements;

Figure 4 is a graphical representation of an example
of electrochemical noise; and

20   Figure 5 is a graphical representation of
electrochemical noise in a concrete structure.

The corrosion monitoring probe of the present
invention has sections of reinforcing steel, generally
referred to herein as elements and preferably formed from

25   the specific steel used for the main reinforcement of the
structure that is to be monitored for effects of
corrosion. The sections of steel are placed in sets of
three with the sets being at increasing distances from
the concrete surface of the structure and preferably

30   supported by plastic tubing which must be both chemically
inert with respect to the concrete and electrically non-
conducting. Each element is independently wired with a
single, suitably insulated, wire. The wire/element
junction should be coated to prevent galvanic corrosion.

35   The wires pass into the tubing, which provides additional
protection during installation. In preferred
embodiments, a length of stainless steel is provided

within the concrete structure, which can be used as a
counter electrode in three electrode measurements, and as
a second electrode for macro cell measurements. In
addition, it is preferred that a stable reference
5   electrode e.g. a Mn/MnO$_2$ electrode, and preferably a
hygrometer and a thermocouple, are also embedded in the
structure. The sets of probe elements at each level are
staggered in position to minimize any effects of
corrosion of the outermost sets on the initiation of
10   corrosion of elements deeper inside the cover of
concrete.

Figure 1 shows a corrosion monitoring probe,
generally indicated by 1. Probe 1 has a plastic tube 2
which, as shown, may be of relatively large diameter
15   compared to other plastic tubing referred to below.
Probe 2 has two foot sections, 3 and 4, that are
interconnected with intermediate section 5. Intermediate
section 5 is shown as extending upwardly from each of
foot sections 3 and 4, and is generally in the shape of
20   an inverted V. However, it will be appreciated that the
shape may be any convenient shape such that intermediate
section 5 is not in the same plane as foot sections 3 and
4.

Intermediate section 5 has a plurality of sets of
25   probe element thereon, indicated by 6A, 6B, 6C, 6D, 6E,
6F and 6G. The sets of probe elements 6A-6G are located
at different heights with respect to the plane of foot
elements 3 and 4. In particular, probe elements 6A
through 6G are at different levels between apex 14 of the
30   inverted V of intermediate section 5, it being understood
that apex 14 could be extending towards an exterior
surface of the concrete structure, as shown in Fig. 1, or
extending away from the exterior surface. Consequently,
the sets of probe elements 6A-6G would be located at
35   different distances from the exterior surface of the
concrete structure. Each of sets of probe elements 6A-6G
has three elements, referred to as 7A, 7B and 7C for

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element 6A. Each of elements 7A, 7B and 7C are located
on the surface of tubing 8, and are at the same distance
from the exterior surface i.e. they are in a plane
parallel to the exterior surface.

5   Tubing 2 and tubing 8 would normally be of different
diameters, although not necessarily so, and are formed
from a material that is chemically inert with respect to
the pore solution within concrete and furthermore which
is electrically non-conductive or is electrically

10   isolated from the probe elements. An example of a
preferred material is a plastic material e.g. polyvinyl
chloride (PVC).

       Wires, not shown in Figure 1, are attached to each
of elements 7A, 7B and 7C, and correspondingly each of

15   the elements in the other sets of probe elements 6B-6G.
The wires pass from each of the individual elements
through tubing 8 into tubing 5. It is to be understood
that in the preferred embodiment of Fig. 1, tubing 8 and
tubing 5 are utilized for passage of electrical wires for

20   protection of the wiring, but that it is not necessary to
do so. In addition, tubing 5 and tubing 8 provides a
convenient method for location and spacing of the sets of
probe elements. The electrical wires are shown as
extending from tubing 5 as an electrical conductor 9

25   having a plurality of wires 10, and would pass to the
exterior of the concrete structure.

       Intermediate section 5 is shown as having a
stainless steel counter electrode extending across the
width of the inverted V. It is to be understood that the

30   counter electrode 11 could be of any suitable material
that is more corrosion resistant than the rebar,
especially substantially more resistant to corrosion
within concrete, and thus may be of materials other than
stainless steel.

35   A hygrometer/thermocouple 12 is shown as attached to
stainless steel counter electrode 11 on one end thereof,
and a reference electrode is shown as attached to the

other end thereof. Hygrometer/thermocouple 12 and
reference electrode 13 may be located at any convenient
location. A typical reference electrode is a Mn/MnO$_2$
electrode.

5   Figure 2 shows a cross-section of a concrete
structure showing an alternate arrangement of the sets of
rebar elements within the concrete structure. Concrete
structure 20 has an exterior surface 21 and a supporting
rebar 22. Located between surface 21 and rebar 22 is
10   support 23, which would be chemically inert and
electrically non-conductive or is electrically isolated
from the probe elements formed of e.g. plastic (PVC)
tubing. Support 23 is shown as having three sets of
rebar 24, 25 and 26. The set 24 of rebar has three
15   elements 24A, 24B and 24C that are in a plane that is
parallel to surface 21 of the concrete. Similarly, set
25 has three elements 25A, 25B and 25C that are also in
the plane of surface 21. Set 26 is similarly
constructed. A plurality of spacers are located between
20   each of the individual elements of the sets of rebar e.g.
between elements 24A, 24B and 24C and support 23, are
similarly located between the individual elements of sets
25 and 26 and rebar 22.

      In a typical example, the sets of the elements would
25   be located at intervals of 5-15 mm between the exterior
surface and the rebar.

      Figure 3 shows a concrete structure 30 having an
exterior surface that has been exposed to a solution 31
containing chloride ions. Section 32 of concrete
30   structure 30 is shown as having three elements of rebar,
indicated by 33A, 33B and 33C, which are located in a
plane parallel to that of the plane of the exterior
surface. Two of the elements 33A and 33B, are shown as
being connected through an ammeter 34 using connections
35   35. Similarly, rebar elements 33B and 33C are shown as
interconnected with a voltmeter 36 and connections 37.
Such a system could be used for the measurement of

electrochemical noise.

A sample of a trace of current noise in microammeters over a period of two hours is shown in Fig. 4 for both stainless steel and carbon steel which
5 have been placed in a synthetic pore solution containing 4% chloride in the form of sodium chloride. Similar behavior is observed for steel embedded in concrete.

Electrochemical current and potential noise traces for probes in cracked and non-cracked regions of a
10 concrete reinforced structure are shown in Figure 5.

When steel reinforcement in concrete corrodes, the iron atoms become ionised releasing electrons which are consumed by the reduction of dissolved oxygen (or, in deaerated or anaerobic concrete, by the evolution of
15 hydrogen).

The flow of electrons between the areas where the anodic and cathodic reactions take place constitutes a current known as the corrosion current. These locations can be adjacent on the atomic level, in which case the
20 cell is known as a micro-cell. At the other extreme, they can be widely separated constituting a macro-cell, for example, the corroding anodic area may be on the top rebar mat of a structure while the bottom of the rebar mat acts as the cathode. The principle is the same in
25 both cases. According to Faraday's law, the corrosion rate, measured in depth of material removed from the surface per unit of time, is related to the corrosion current as follows:

$$d = \frac{i \,.t. \, A}{n \,.F. \, \rho}$$

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where "d" is the depth of corrosion in $\mu m/year$; "i" is the corrosion current density in $\mu A/cm^2$; "t" is the time in seconds; "A", "n" and "ρ" are the atomic mass,
35 the valency and the density of iron, respectively and "F" is Faraday's constant (96,500 coulombs/equivalent). As an example, a corrosion current is 1 $\mu A/cm^2$ would be

equivalent to a corrosion rate of 11.6 μm/year dissolving or oxidizing from the steel surface.

Using these principles, and the probe elements installed in the concrete as described herein, a number
5   of electrochemical techniques can be used to monitor the corrosion, including half cell potential, macro-cell current, linear polarization resistance, and electrochemical noise.

One or more of these techniques may be employed to
10   continuously monitor the probe elements, which would allow variations in corrosion behaviour with ambient temperature and relative humidity to be determined. Since the data will be received as electrical signals, it can be transmitted to a remote location for analysis.

15   One technique for measurement of rebar corrosion damage is the measurement of half cell potential. Such a measurement procedure is described in ASTM C876-80, which uses a reference electrical and an electrical connector to the rebar. The basis of the test is that
20   the corrosion potential of the rebar will shift in the negative direction if the surface changes from the passive or non-corroding state to the active or corroding state.

In the measurement of half cell potential mapping
25   using the present invention, either the reference electrode (indicated by 13 in Fig. 1) or the stainless steel bar incorporated in the probes (indicated by 11 in Fig. 1) can act as a reference electrode and the potential difference between each probe element, and
30   either the reference electrode or the stainless steel bar can be used as half-cell potential. Such a technique is simple, but the results obtained are qualitative, and no actual rebar corrosion rate is established. Furthermore, results obtained can be misleading e.g. data suggestive
35   of corrosion may be recorded in submerged concrete structures where the corrosion rate is negligible due to the absence of oxygen.

A second technique is the macro-cell current technique, also known as the zero resistance ammetry, which measures the current flowing between individual embedded probe elements and the stainless steel bar, and
5   serves as a more quantitative indication of corrosion than half cell potential. The stainless steel will act as the cathode of a galvanic cell with the probe element acting as the anode. When chlorides penetrate to the level of the probe element and initiate active corrosion,
10   the current flowing between the rebar and the stainless steel will increase significantly, typically by more than two order of magnitude. The principle of macro-cell current technique is used in ASTM G102-92 corrosion test procedure, where the current flows between rebar embedded
15   near a surface exposed to chlorides and rebar at greater depths of cover.

The concept of measuring a macro-cell current as indicator of corrosion severity may also be applied using two of the three probe elements of each set described
20   herein. However, the magnitude of the current will tend to be lower than that obtained using one rebar element and the stainless steel, particularly if both rebar elements are corroding.

Under natural, equilibrium corrosion conditions, the
25   number of electrons released by the anodic reaction is exactly equal to that consumed by the cathodic reactions. Therefore, there is no net current which can be measured. In order to determine the corrosion current, the system must be biased away from equilibrium and the resulting
30   net current is then measured. In corrosion, the current and electrochemical potential are proportional for small (≤ 20 mV) deviations from equilibrium. Therefore, in this range of potential, the system can be biased by applying a potential, ΔE and measuring the resultant current, Δi,
35   (potentiostatic control), or by applying a current and measuring the resultant potential gradient (galvanostatic control).

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The ratio ($\Delta i/\Delta E$) is termed the Polarization Resistance, R_p, as described in ASTM 659, and is related to the actual corrosion current, i_{corr} by the relationship:

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$$i_{corr} = \frac{B}{Rp}$$

where B is a constant of the order of 30mV.

While this technique does give a significant indication of corrosion rate, it is not a passive

10   technique: a potential (or current) must be applied between the probe elements and the resultant current (or potential) measured.

Unlike the other electrochemical techniques, electrochemical noise measurements do not rely on any

15   "artificial" signal imposed on a rebar probe element or establishment of an artificial galvanic cell. In contrast, natural fluctuations in the corrosion potential and current are monitored to characterize the severity and type of corrosive attack, which requires a three

20   electrode system for simultaneous measurement of current potential and current noise. The three nominally identical rebar probe elements of each set are used for such measurement.

For electrochemical noise measurements on rebar

25   probes embedded in concrete, sensitive instrumentation is required, for example with minimum current and potential resolution levels around 0.1 µA and 0.1 mV respectively. The current and potential noise levels tend to increase with increasing electrochemical activity on the rebar

30   surface. Furthermore, the noise data can be particularly useful for identifying the initiation and propagation of corrosion pits, a distinct advantage over all of the other techniques. The noise transients characteristics of rebar pit initiation and repassivation on a

35   microscopic scale are illustrated in Fig. 4 and 5. These "signatures" of the initiation of corrosion pits are evident long before the attack is observable by visual means, or detectable by other electrochemical techniques,

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indicating the "early warning" capabilities of this sensitive technique.

The corrosion monitoring probe of the present invention utilizes sets or groups of three rebar elements
5 at the same depth within the concrete, with a plurality of sets at different depths. It is to be understood that more than three such elements could be utilized in each set for additional measurements although it is not necessary to do so. However, the sets of rebar elements
10 must have at least three rebar elements for the measurements described herein.

The corrosion surveillance system of the present invention permits prediction of (i) when, in the absence of any remedial treatment, corrosion will start, and (ii)
15 the rate of corrosion after initiation. This will allow maintenance and rehabilitation processes to be scheduled in advance and suitable corrosion protection systems to be installed at an appropriate time. Such a system may be designed to allow the progress of chloride penetration
20 through the concrete cover to be monitored and, thereby, to predict when corrosion of the main rebar will be initiated. By constructing the probe elements from the same steel as the rebar, the actual corrosion rates after initiation can be determined and applied to protect the
25 life of the structure.

The present invention provides a versatile concrete monitoring probe system that is capable of being utilized for a wide variety of measurements. It is understood that such elements would be embedded in the concrete at
30 the time of erection of the structure, immediately prior to pouring of the concrete, but once installed could not be relocated, inserted, repaired or otherwise disturbed, as any such disturbance would negate any subsequent measurements of corrosion or potential corrosion.

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CLAIMS:

1.   A corrosion measuring system for assessing the onset
and the rate of corrosion of reinforcing steel embedded
in a concrete structure having an exterior surface,
comprising:

(a)   a set of at least three elements formed from
reinforcing steel and located in a spaced apart
relationship at the same depth from said exterior
surface;

(b)   each of said elements having electrical
connections extending therefrom through said exterior
surface, said electrical connections being adapted for
connection to apparatus for measurement of
electrochemical properties of said elements for
assessment of corrosion of said reinforcing steel.

2.   The corrosion measuring system of Claim 1 in which
there is additionally at least one element of electrical
conductive material less susceptible to corrosion in said
concrete, said electrical conductive material being
embedded in said concrete and having an electrical
connection extending through said exterior surface
adapted for connection to said apparatus.

3.   The corrosion measuring system of Claim 1 or Claim 2
in which there are more than one set of said at least
three elements, each of said sets of at least three
elements being located at differing distances from said
exterior surface.

4.   The corrosion measuring system of any one of Claims
1-3 in which said elements are located on corrosion-
resistant electrically non-conductive supports.

5.   The corrosion measuring system of Claim 4 in which
said electrically non-conducting supports are further

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supported by a second electrically non-conductive tubular
support that is attached to said reinforcing steel, said
electrical connections passing through said second
tubular support to said exterior surface.

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6.   The corrosion measuring system of Claim 4 or Claim 5
in which said supports are tubular and said electrical
connections pass through said tubular support.

10   7.   The corrosion measuring system of any one of Claims
1-6 in which a reference electrode is embedded in the
concrete.

8.   The corrosion measuring system of any one of Claims
15   1-7 in which a hygrometer is embedded in the concrete.

9.   The corrosion measuring system of any one of Claims
1-8 in which the distance between adjacent sets of
elements is 5-15 mm, as measured from said exterior
20   surface.

10.   The corrosion measuring system of any one of Claims
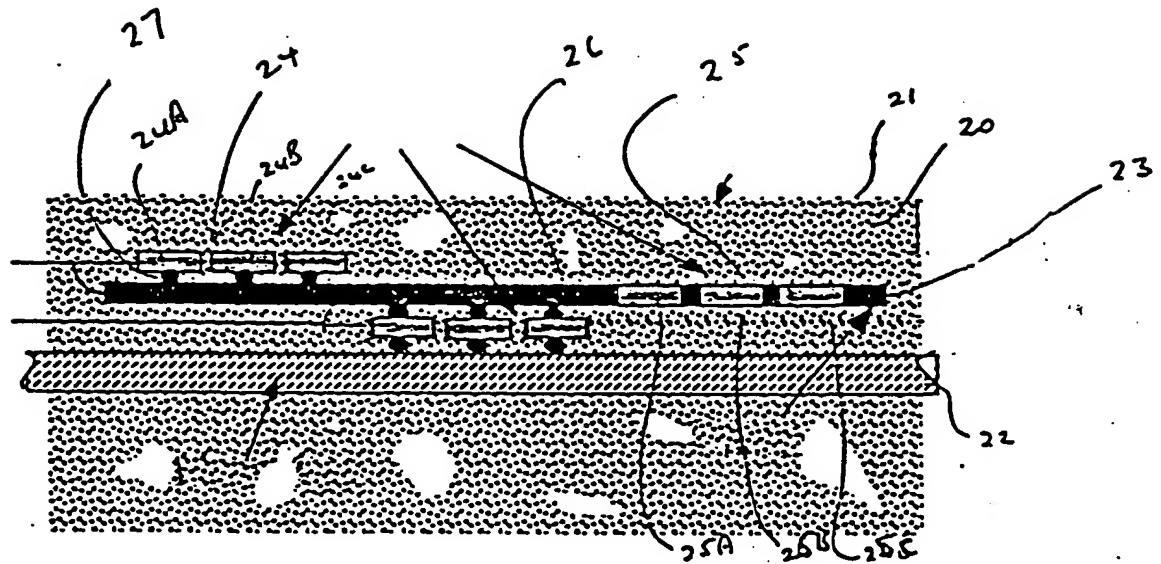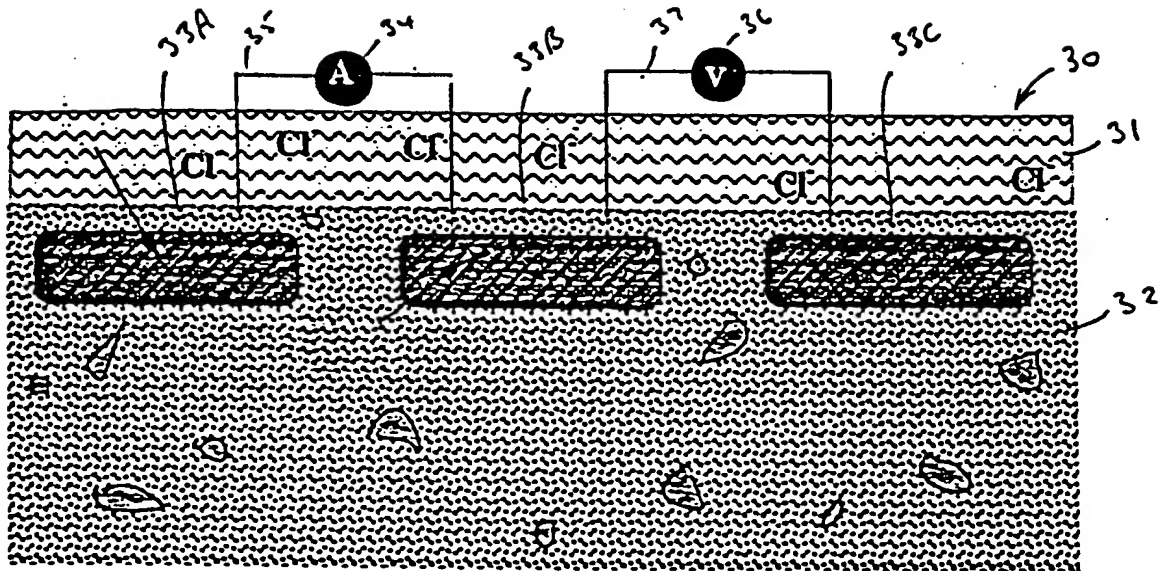1-9 in which each set has three elements.

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FIG. 1
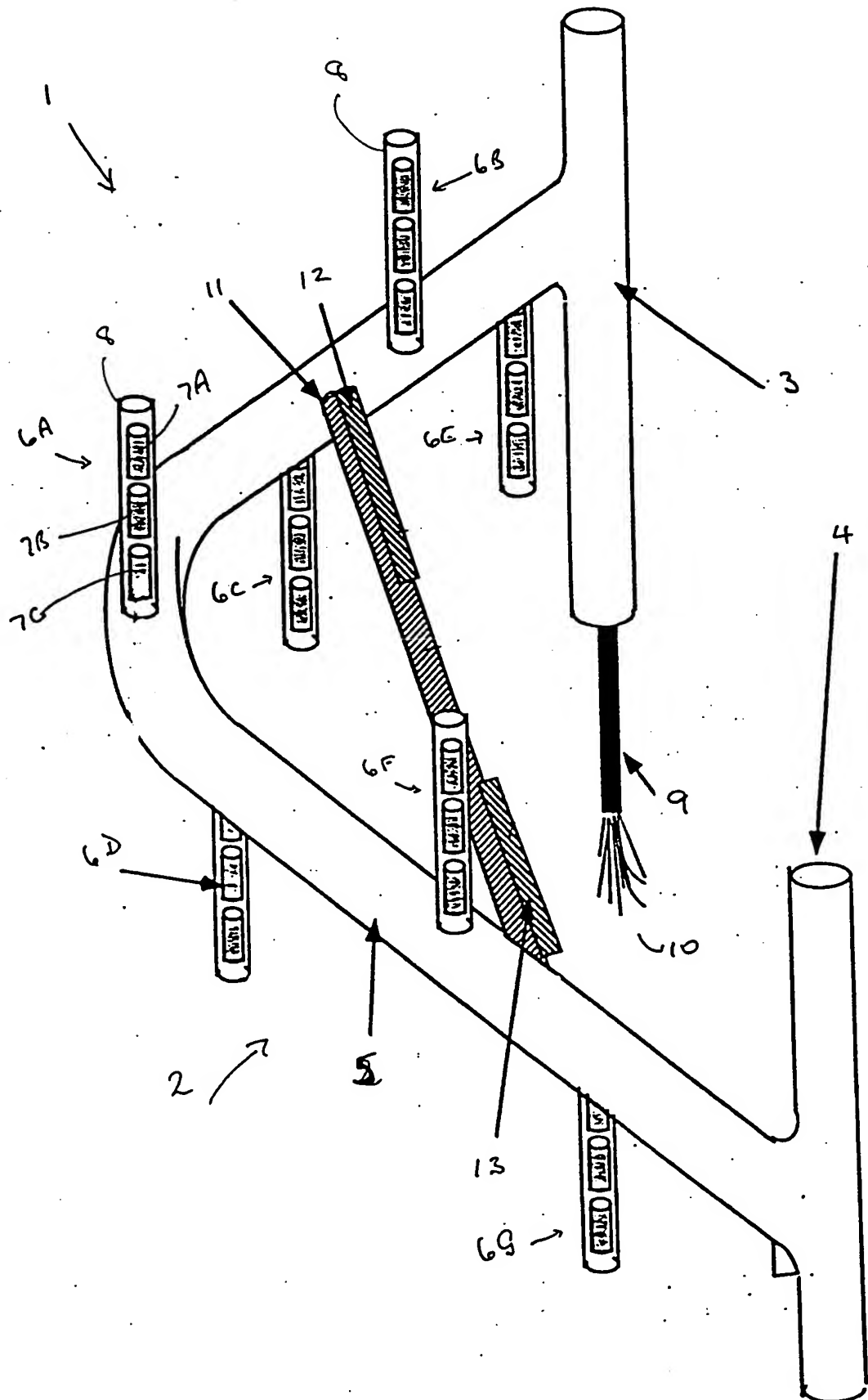
FIG. 2

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FIG. 3

FIG. 4

FIG. 5